DETECTION, LOCATION, AND CLASSIFICATION OF SPACE SHUTTLE MAIN ENGINE NOZZLE LEAKS BY TRANSIENT THERMOGRAPHIC INSPECTION

Samuel S. Russell
Nondestructive Evaluation Team
NASA Marshall Space Flight Center
256-544-4411
sam.russell@msfc.nasa.gov

James L. Walker
Center for Automation and Robotics
University of Alabama in Huntsville
256-890-6578 ext. 207
walkerj@email.uah.edu

ABSTRACT

Leak checking and evaluation of pressure vessels by observing the slight temperature changes resulting from structural anomalies has been made possible through developments in high resolution infrared cameras and advanced image processing. These developments have made thermal nondestructive analysis a very practical and efficient method to determine material consistency and structural quality as well as monitor processes.

The Space Shuttle Main Engine Nozzle has regions which can not be inspected with standard leak check methods. The Thermographic methods being developed to nondestructively test the Nozzle for leaks in inaccessible regions are reported. Also, a flash heating Thermographic investigation of the braze line bonding the cooling tubes to the outer structural jacket of the nozzle is reported.

INTRODUCTION

Modern infrared video cameras are capable of measuring temperature differences of less than 0.025°C. Using this extreme detection capability and creative digital image processing methods to control noise, Thermography can solve many nondestructive evaluation problems. Inspection methods based upon resolving rapid transient thermal processes in particular are made possible. This has allowed inspection of material by flash heating with photographic flash lamps and observing the thermal response images at every 0.017 seconds per frame. Also, this instrumentation allows the visualization of minute surface temperature changes due to some internal process mapped upon a geometric image of a part. Two examples of using Thermographic methods to solve inspection problems with the Space Shuttle Main Engine Nozzle are investigated and reported. One of these problems, interstitial leaking, has no other nondestructive solution.

The nozzles of the Space Shuttle's Main Engines (SSME) consist of 1080 tapered Inconel coolant tubes brazed to an A-286 structural jacket (Figure 1). Three potential problems occur within the SSME Nozzle coolant tubes as a result of manufacturing anomalies and the highly volatile service environment. The problems include poor or incomplete brazing of the tubes to the structural jacket, tubes that leak into the interstitial zone, and tubes that leak into the flame surface (hot wall). The hot wall leaks are accessible, and are easily identified, located, and classified by the application of a liquid leak check solution and visual inspection.

Inspections for determining braze line integrity can be performed by standard x-ray practices. The problem though is that the process of performing an x-ray inspection on the entire nozzle is very labor intensive and expensive. A proposed alternative to locate the unbond is flash thermography from the outer (cold wall) side of the nozzle. In regions were the jacket is exposed, so that it can be flash heated, the potential to map the braze integrity exists. The regions obscured by hat bands and external plumbing will still have to be inspected using x-ray techniques.

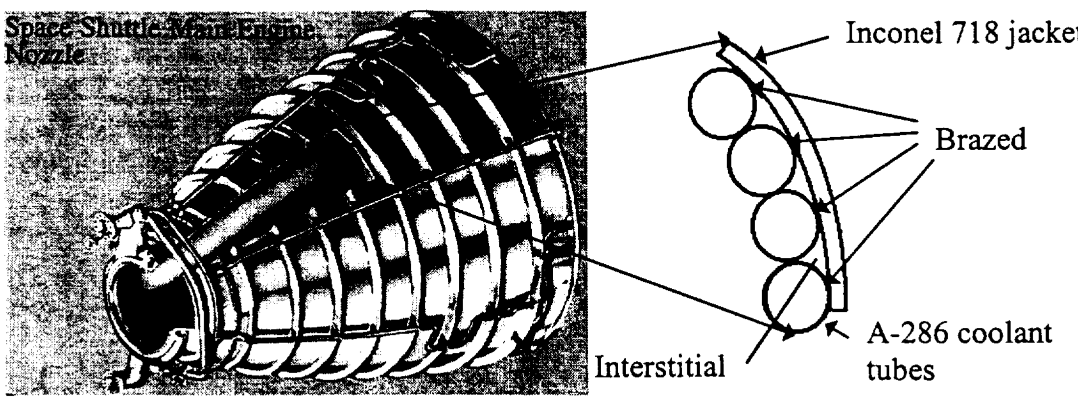


Figure 1. SSME Nozzle with cutaway showing cooling tubes and outer structural jacket.

DISBOND BETWEEN TUBES AND JACKET

Initial experiments were performed to determine if it was possible to identify disbonds between the coolant tubes and structural jacket of the SSME nozzle. The disbond was simulated by milling out a portion of the tubing with a moto-tool from the hot wall side of the nozzle. The defect tapered from a 1 inch opening at the inner surface of the nozzle to the brazed edge of the skin. Although this did not produce a true disbond, the artificial defect did demonstrate the same thermal behavior that a disbond, i.e. both have the effect of reducing the effective flow path of heat. The artificial defect was easily detected.

An SSME nozzle segment was then inspected by flash heating its cold wall side using an Amber Radiance 1t camera (25 mm lens) running under Thermal Wave Inc. software. Figure 2 shows the apparatus in place during the inspection of the nozzle. The flash unit and infrared camera were mounted on a tripod with the flash hood against the part and the camera imaging the part through the hood. Flash Thermography images were acquired by viewing the jacket side of the nozzle after flash heating the same side. Areas of greatest structural integrity conducted the heat away from the jacket quite well, and appear dark in these images. Areas containing discontinuities (such as the programmed defect or the interstitial gaps between the cooling tubes and jacket) did not conduct the heat away from the jacket as well, and appear bright in these images. Figure 3 shows a region of large unbraze between the tubes and the structural jacket due to a manufacturing defect in a nozzle. However, large regions of the nozzle can not be inspected using Flash Thermography due to the interference of structural stiffeners, insulation, or piping. But, mapping of braze integrity in the open bays is possible.

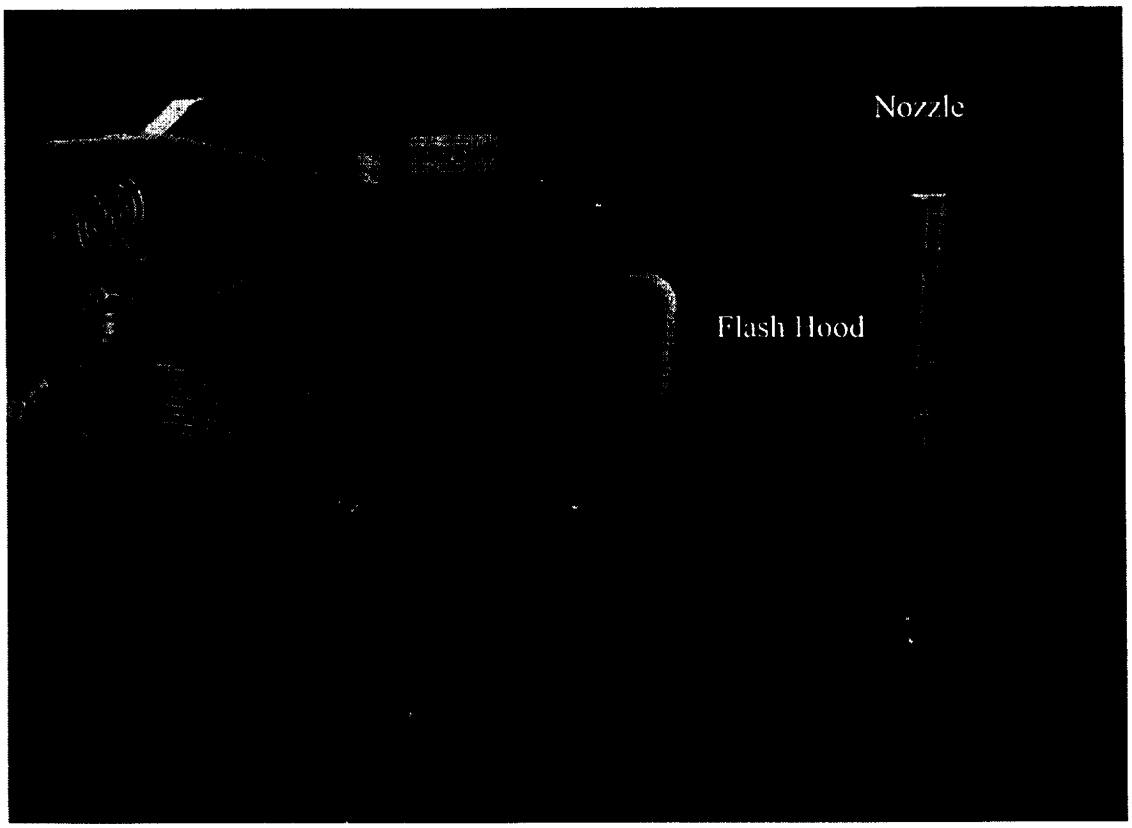


Figure 2. Flash Thermography Equipment Interrogating an SSME nozzle.

LEAK DETECTION PROBLEM

The origin of leaks into the interstitial zone can not be determined with leak check solution or other traditional nondestructive methods. Due to the geometry and location of the defects, eddy current and visual inspections are not possible and the crack or pin hole responsible for the leak is normally too small for radiographic, ultrasonic, or computed tomographic detection. The current inspection technique for locating interstitial leaking is the application of leak check solution in the openings where the interstitials vent below the bottom of the nozzle, while the tubes are pressurized to 25 psig. When a leak is found, it is classified, and if the leak is severe enough the suspect tube is cut open so that a boroscope can be inserted to find the leak point. Since the boroscope can only cover a finite tube length and since it is impossible to identify which tube (to the right or left of the identified interstitial) is leaking, many extra and undesired repairs must be made to fix

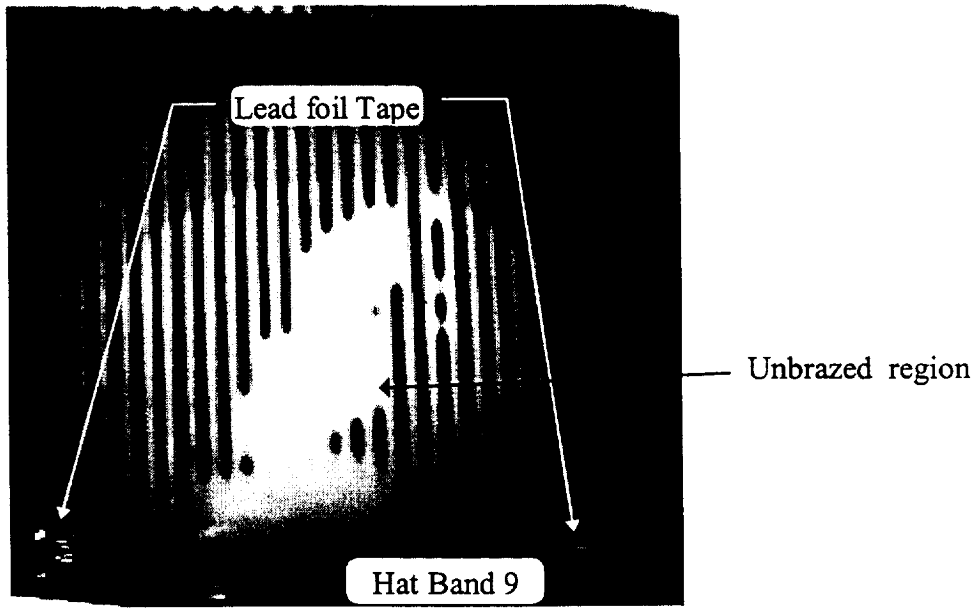


Figure 3. Flash Thermography of unbrazed area.

just one leak. In certain instances when the interstitials are interlinked by poor braze bonding, many interstitials will show indications of leaking from a single source. What is desired is a technique that can identify the leak source so that a single repair can be performed. The leaks of interest are classified in four categories as described in the following Table. It was proposed to try thermographic methods to locate the interstitial leak, from the hot wall side of the nozzle, by detecting the local cooling created by escaping gas at the location of a defect.

	Volume rate in scim based upon 25 psig Helium	Description using a certain leak check solution
Class I	0.001-1.3	Foaming
Class II	1.2 - 4.0	Random size bubbles of moderate persistence
Class III	4.0 -50	Large fast-forming bubbles of short persistance most of which break as the next forms.
Blower	Greater than 50	Blowing (Bubbles do not form because of large gas flow)

THERMOGRAPHY FOR LEAK DETECTION

Artificial defects were fabricated into a nozzle segment cut from the lower region of a scrap SSME nozzle including the eighth and ninth hat bands. By cutting open the tubing on the hot wall side of the nozzle, then puncturing the tube into the interstitial region and finally resealing the tube with a cover patch through a welding operation, phantom defects were fabricated, see Figure 4. The leak type and interstitial location were determined by individually pressurizing each tube and checking with leak solution.

In all cases no surface leaks were detected with leak check solution. For brevity only results for Region 1 are presented.

During the reweld operation the hot wall surface of the tubes had to be cleaned with a wire brush. This left the surface shiny, which greatly limited the thermographic inspection capability. To dull the surface it was painted with three coats of a water washable flat black paint. The paint was applied by first heating the metal surface with a hot air gun, applying a light coat of paint, and then reheating the surface to speed evaporation of the water carrier. This process provided a consistent finish and permits a thinner coat of paint be applied and still have adequate dulling of the surface. The normal, as fired, surface of the nozzle has an emissivity high enough so that no surface treatment is required.

Figures 5 shows the resulting Thermograms over 4 time intervals obtained by rapidly pressurizing the nozzle segment to 40psig (less than 2 seconds to reach maximum pressure) with Nitrogen gas. These Thermograms were made by subtracting an image prior to pressurization from the later images. Hence, the temperature change is accented. Also included (Figure 6) is the Time-Temperature plot for four points on the image which provide an indication of the degree to which the defects can be detected. By re-running the test at several pressure levels, it was determined that the temperature change observed at a leak source increased approximately linearly with increasing pressure. Also, it was determined experimentally that Nitrogen and Argon gas produced larger thermal indications as compared to the Helium gas used for the liquid leak check investigations.

A second panel cut from the upper end of a nozzle was prepared with artificial weld defects that were classified as Class II and Class III as shown in Figure 7. The cooling tubes grow continuously from the top to the bottom of the nozzle creating a some what different problem at the top because of the much smaller tubes and interstitials. The Thermograms generated by rapidly (< 2 seconds) pressurizing the segment with 40 psig Nitrogen are shown in Figure 8. The difference between a Class II leak on the right and a Class III on the left is very apparent.

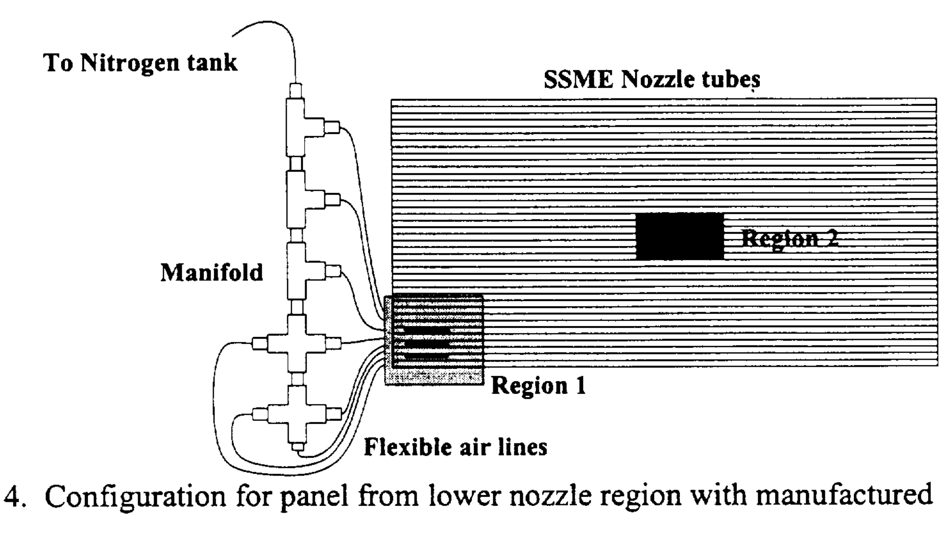
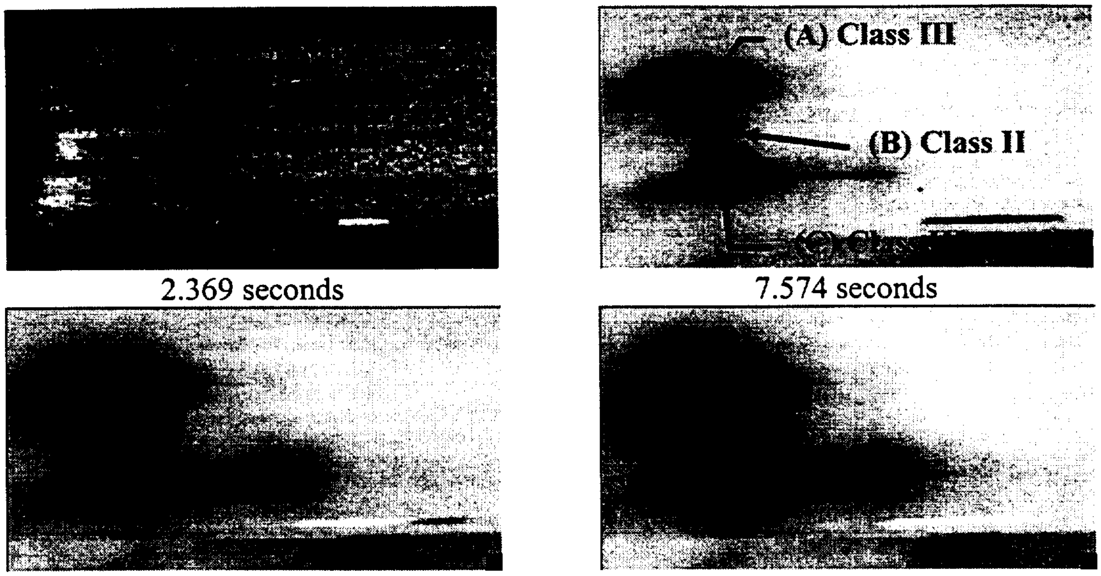


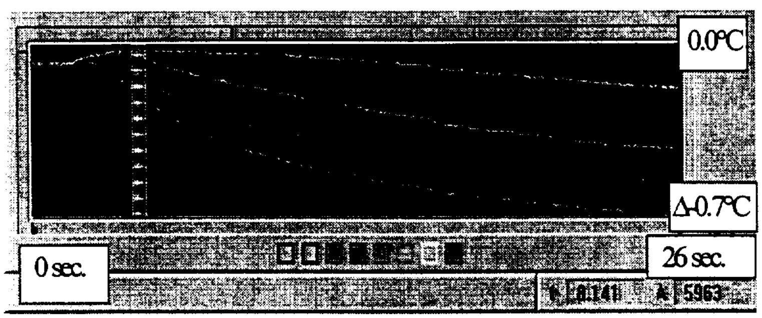
Figure 4. Configuration for panel from lower nozzle region with manufactured leaks.

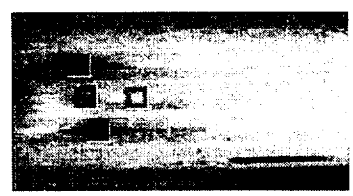


2.369 seconds 7.574 seconds

16.583 seconds 25.092 seconds

Figure 5. Thermograms of Region 1 of panel shown in Fig. 4.





Locations and colors correspond to left chart.

Figure 6. Time vs. Temperature for Class II and Class III leaks in test panel.

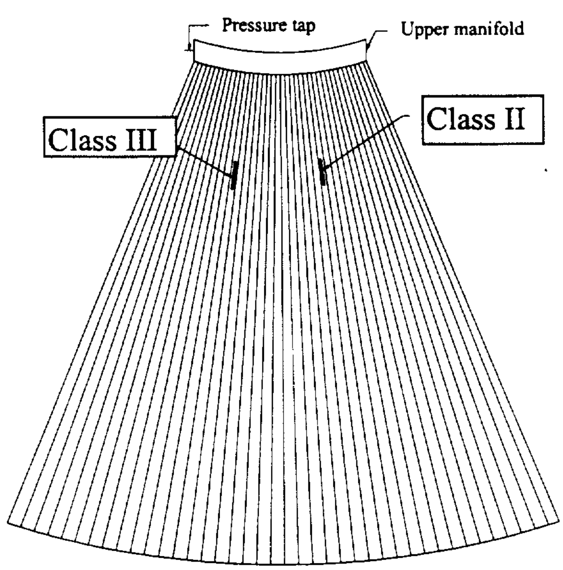
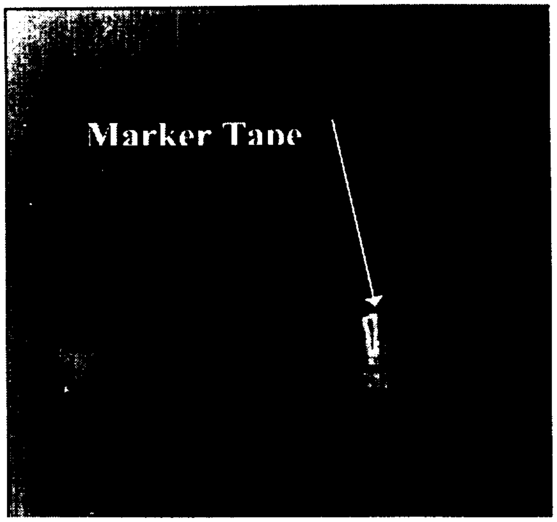
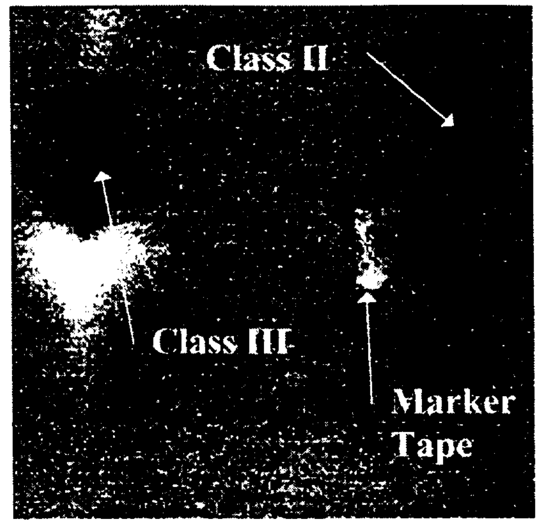


Figure 7. Location of defects in panel cut from the upper portion of a nozzle.





Original image Image (ΔT) difference

Figure 8. Thermogram of leaks in panel cut from upper portion of nozzle.

FULL SCALE SSME NOZZLE INSPECTION

An SSME Nozzle which contained a Class II interstitial leak was inspected at the manufacturing facility. Weld repairs were painted with three coats of water washable flat black paint as previously described for the nozzle segments. The nozzle was pressurized with Argon gas from a standard welding "K" bottle. The general radial location had been determined with a leak check solution and was marked with brass foil tape, placed on 6 inch centers from the forward manifold, to track image location. The pressurization with Argon took an average of 16 to 20 seconds to reach the desired 40 psig level. This is a much slower pressurization rate than that utilized for the experiments run on the panel segments cut from a scrap nozzle. Faster pressurization was possible in the proof pressurization test cell, but it was not available for these tests.

As shown in the Figures 9, a leak indication was found under the cover patch of a previously repaired location. It was not possible with the slower pressurization rate to define which tube under the cover patch was leaking. Due to the slow thermal transient, the effects of the leak dissipated into the heavy cover patch before its source could be pinpointed. There was though, a thermal indication of the effects of the leak at the cover patch seen in the tubes above the suspect area. Here, due to the increased flow rate, the tube with the leak appears to be colder than its neighbors. By zooming in on the region of the tubes where they enter the upper manifold it was possible to identify two tubes (labeled A and B) that appear to be cooler "leaking". These tubes are shown in Figure 10, and have been marked on the nozzle with foil tape. The nozzle manufacturer now knows the location of the leak and can open those tubes and repair them.

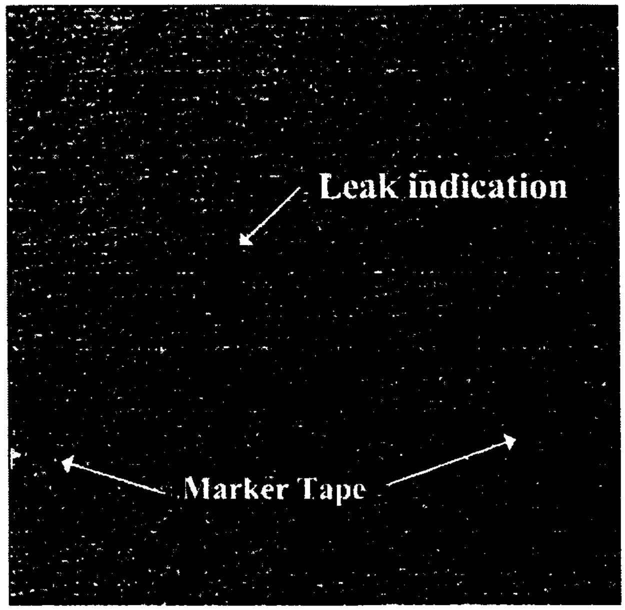


Figure 9. Thermogram of SSME Nozzle with Argon pressurization, ≈ 18 sec time to 40 psig).
Thermal indication (0.084 °ΔC)

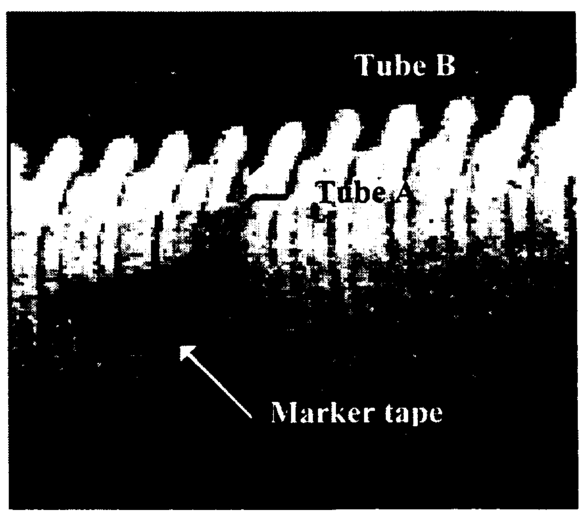


Figure 10. Thermogram of upper edge of nozzle showing leaking tubes.

CONCLUSION

- Thermography can locate and classify leaks that occur in the interstitial locations of the Space Shuttle Main Engine Nozzle. Prior to this method no means of nondestructively inspecting interstitial leaks existed.

- Braze integrity between the hat stiffener and structural jacket can be determined on the Space Shuttle Main Engine Nozzle with Flash Thermography.

- Due to increased thermal sensitivity and advances in image processing techniques many problems in material testing or process verification may be solved with modern video Thermographic methods.

ACKNOWLEDGMENTS

Messieurs Albert Avila, Al Bernat, Caleb Branscomb, Gary Schock Ron Daniel and Ben Coby of Boeing for the excellent support at Canoga Park, CA and very especially Messieurs Paul Caraccioli and Melvin Bryant of NASA/MSFC for their patience in explaining the problem and for help coordinating activities with Boeing.